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HIGH STEAM-PRESSURES IN LOCOMOTIVE SERVICE

(A REVIEW OF A REPORT TO THE CARNEGIE INSTITUTION OF WASHINGTON)

BY

W. F. M. GOSS

UNIVERSITY OF ILLINOIS

ENGINEERING EXPERIMENT STATION

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HIGH STEAM-PRESSURES IN LOCOMOTIVE SERVICE

PREFACE

The *Report on High Steam-Pressures in Locomotive Service*, issued by the Carnegie Institution of Washington as Serial No. 66, is a publication of 144 pages dealing with a research which was carried on in the laboratory of Purdue University during the writer's connection with that University. It illustrates and describes the locomotive and other apparatus employed, and presents in tabulated and graphical form the full record of observed and derived results. In this Review, the text of the Report has been freely quoted, and the conclusions and arguments by which they are sustained appear as given in the original publication. The Review, therefore, takes the form of a résumé of the research and its results, the complete record of which is available elsewhere.

In the editorial work incident to the preparation of this Review, Mr. Paul Diserens has had an important share.

W. F. M. G.

December, 1908.

UNIVERSITY OF ILLINOIS

ENGINEERING EXPERIMENT STATION

BULLETIN NO. 26 SEPTEMBER 1908

HIGH STEAM-PRESSURES IN LOCOMOTIVE SERVICE

(A Review of a Report to the Carnegie Institution of Washington)

BY W. F. M. GOSS, DEAN OF THE COLLEGE OF ENGINEERING AND DIRECTOR OF THE SCHOOL OF RAILWAY ENGINEERING AND ADMINISTRATION

INTRODUCTION

A SUMMARY OF CONCLUSIONS

The results of the study concerning the value of high steam-pressures in locomotive service, the details of which are presented in succeeding pages, may be summarized as follows:

1. The results apply only to practice involving single-expansion locomotives using saturated steam. Pressures specified are to be accepted as running pressures. They are not necessarily those at which safety valves open.

2. Tests have been made to determine the performance of a typical locomotive when operating under a variety of conditions with reference to speed, power, and steam-pressure. The results of one hundred such tests have been recorded.

3. The steam consumption under normal conditions of running has been established as follows:

Boiler pressure 120 lb., steam per indicated horse-power hour 29.1 lb.
Boiler pressure 140 lb., steam per indicated horse-power hour 27.7 lb.
Boiler pressure 160 lb., steam per indicated horse-power hour 26.6 lb.
Boiler pressure 180 lb., steam per indicated horse-power hour 26.0 lb.
Boiler pressure 200 lb., steam per indicated horse-power hour 25.5 lb.
Boiler pressure 220 lb., steam per indicated horse-power hour 25.1 lb.
Boiler pressure 240 lb., steam per indicated horse-power hour 24.7 lb.

4. The results show that the higher the pressure, the smaller the possible gain resulting from a given increment of pressure. An increase of pressure from 160 to 200 lb. results in a saving of 1.1 lb. of steam per horse-power hour, while a similar change from 200 lb. to 240 lb. improves the performance only to the extent of 0.8 lb. per horse-power hour.

5. The coal consumption under normal conditions of running has been established as follows:

Boiler pressure 120 lb., coal per indicated horse-power hour 4.00 lb.
Boiler pressure 140 lb., coal per indicated horse-power hour 3.77 lb.
Boiler pressure 160 lb., coal per indicated horse-power hour 3.59 lb.
Boiler pressure 180 lb., coal per indicated horse-power hour 3.50 lb.
Boiler pressure 200 lb., coal per indicated horse-power hour 3.43 lb.
Boiler pressure 220 lb., coal per indicated horse-power hour 3.37 lb.
Boiler pressure 240 lb., coal per indicated horse-power hour 3.31 lb.

6. An increase of pressure from 160 to 200 lb. results in a saving of 0.16 lb. of coal per horse-power hour, while a similar change from 200 to 240 lb. results in a saving of but 0.12 lb.

7. Under service conditions, the improvement in performance with increase of pressure will depend upon the degree of perfection attending the maintenance of the locomotive. The values quoted in the preceding paragraphs assume a high order of maintenance. If this is lacking, it may easily happen that the saving which is anticipated through the adoption of higher pressures will entirely disappear.

8. The difficulties to be met in the maintenance both of boiler and cylinders increase with increase of pressure.

9. The results supply an accurate measure by which to determine the advantage of increasing the capacity of a boiler. For the development of a given power, any increase in boiler capacity brings its return in improved performance without adding to the cost of maintenance or opening any new avenues for incidental losses. As a means to improvement, it is more certain than that which is offered by increase of pressure.

10. As the scale of pressure is ascended, an opportunity to further increase the weight of a locomotive should in many cases find expression in the design of a boiler of increased capacity rather than in one for higher pressures.

11. Assuming 180 lb. pressure to have been accepted as standard, and assuming the maintenance to be of the highest order, it

will be found good practice to utilize any allowable increase in weight by providing a larger boiler rather than by providing a stronger boiler to permit higher pressures.

12. Wherever the maintenance is not of the highest order, the standard running pressure should be below 180 lb.

13. Wherever the water which must be used in boilers contains foaming or scale-making admixtures, best results are likely to be secured by fixing the running pressure below the limit of 180 lb.

14. A simple locomotive using saturated steam will render good and efficient service when the running pressure is as low as 160 lb.; under most favorable conditions, no argument is to be found in the economic performance of the engine which can justify the use of pressures greater than 200 lb.

HIGH STEAM-PRESSURES IN LOCOMOTIVE SERVICE

I. The Research and the Means Employed in Its Advancement

1. *Steam-Pressures in Locomotive Service.*—For many years past there has been a gradual but nevertheless a steady increase in the pressure of steam employed in American locomotive service. Between 1860 and 1870 a pressure of 100 lb. per sq. in. was common. Before 1890 practice had carried the limit beyond 150 lb. At the present time 200 lb. is most common, but an occasional resort to pressures above this limit suggests a disposition to exceed it.

High steam-pressure does not necessarily imply high power. It is but one of the factors upon which power depends. The forces which are set up by the action of the engine are as much dependent upon cylinder volume as upon boiler-pressure, and when the pressure is once determined the cylinders may be designed for any power. The limit in any case is to be found when the boiler can no longer generate sufficient steam to supply them. The relation between pressure and power is therefore only an indirect one. But anything which makes the boiler of a locomotive more efficient in the generation of steam, or the engines more economical in their use of steam, will permit an extension in the limit of power. If, for example, it can be shown that higher steam-pressure promotes economy in the use of steam, higher steam-pressure at once becomes an indirect means for increasing power. The fact to be emphasized is that an argument in favor of higher steam-pressures must concern itself with the effects produced upon the economic performance of the boiler or engine.

2. *Preparations for an Experimental Study.*—In view of the facts stated, and with the hope of ascertaining a logical basis from which to determine what the pressure should be for a sim-

ple locomotive, using saturated steam, it was long ago determined to undertake an experimental study of the problem upon the testing plant of Purdue University. A few experiments involving the use of different steam-pressures in locomotive service were made at Purdue as early as 1895, but as the boiler of the locomotive then upon the testing-plant was not capable of withstanding pressures greater than 150 lb., these early tests were limited in their scope.[1] The matter was, however, regarded as of such importance that in designing a new locomotive for use upon the plant, a pressure of 250 lb. was specified—a limit which then was and still is considerably in advance of practice. Thus equipped, an elaborate investigation was outlined, involving a series of tests under six different pressures, representing a sufficient number of different speeds and cut-offs to define the performance of the locomotive under a great range of conditions. But the expense of operating the locomotive under very high steam-pressures proved to be so great that the limited funds which could be devoted to the operations of the laboratory, in combination with the demands of students, which could be most easily satisfied by work under lower pressures, made it impracticable for a time to proceed with the work. A grant from the Carnegie Institution of Washington was announced late in the fall of 1903. The first test in the Carnegie series was run February 15, 1904, and the last August 7, 1905. A registering counter attached to the locomotive shows that between these dates the locomotive drivers made 3,113,333 revolutions, which is equivalent to 14,072 miles.

3. *The Tests.*—The tests outlined included a series of runs for which the average pressure was to be, respectively, 240, 220, 200, 180, 160, and 120 lb., a range which extends far below and well above pressures which are common in present practice. It was planned to have the tests of each series sufficiently numerous to define completely the performance of the engine when operated under a number of different speeds and when using steam in the cylinders under several degrees of expansion. As far as practicable, each test was to be of sufficient duration to permit the efficiency of the engine and boiler to be accurately determined, but where this could not be done cards were to be taken. A precise statement of the conditions under which, in the development of

[1] Results of these tests will be found published in Locomotive Performance. John Wiley & Sons.

this plan, the tests were actually run, is set forth diagrammatically in Fig. 1 to 6 accompanying, in which vertical distances represent speed, and horizontal distances the point of cut-off as determined by the notch occupied by the latch of the reverse lever, counting from the center forward. Each complete circle in these diagrams represents an efficiency test, and each dotted circle, a shorter test under conditions involving the development of power in excess of that which could be constantly sustained. The numerals within the circles refer to the laboratory numbers by which the several tests are identified.

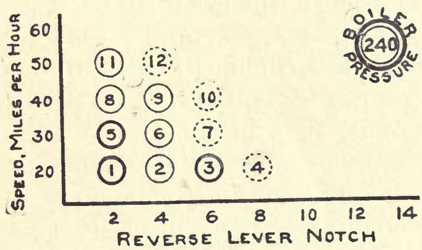

FIG. 1

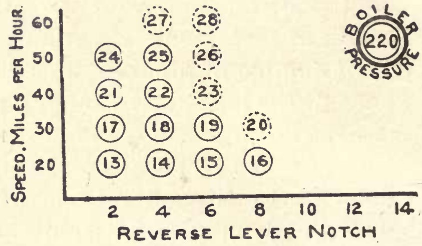

FIG. 2

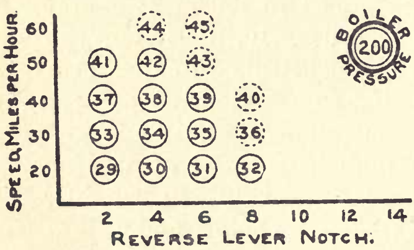

FIG. 3

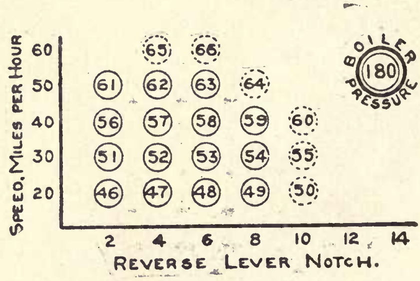

FIG. 4

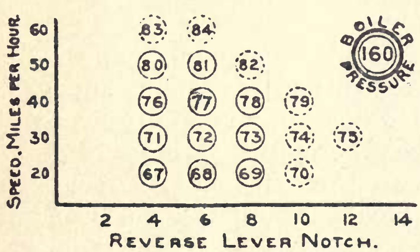

FIG. 5

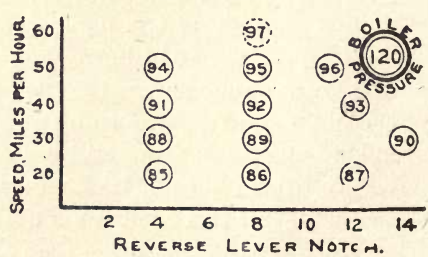

FIG. 6

4. *The locomotive upon which the tests* were made is that regularly employed in the laboratory of Purdue University, where it is known as *Schenectady No. 2.* It was ordered of the Schenectady Locomotive Works in 1897. In selecting a second locomotive which should serve the purposes of the Purdue testing-plant, it was decided to have the boiler of substantially the same capacity as that of the locomotive previously employed in the laboratory and which in later years has been known as *Schenectady No. 1.* In some other respects the new locomotive differed from its predecessor. Its boiler was designed to operate under pressures as high as 250 lb., a limit which was then 25 per cent higher than the maximum employed in practice. Horizontal seams are butt-jointed with welt strips inside and out, and are sextuple-riveted. The design of its cylinders and saddle is such as readily to permit the conversion of the simple engine into a two-cylinder compound. The driving-wheels of the new locomotive are of larger diameter than those of *Schenectady No. 1.*

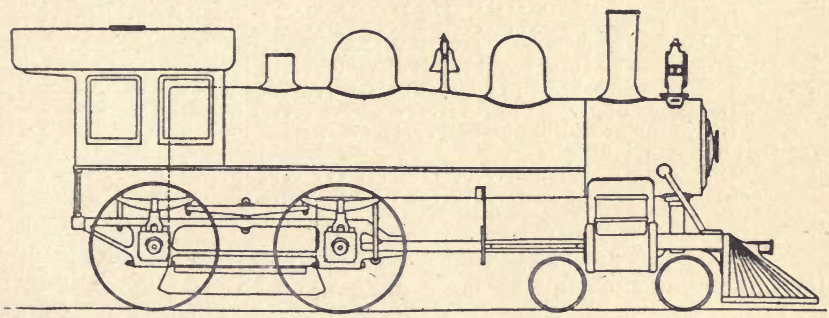

FIG. 7 OUTLINE ELEVATION OF LOCOMOTIVE

The principal characteristics of the locomotive are as follows:

Type		4-4-0
Total weight	pounds	109 000
Weight on four drivers	pounds	61 000
Valves: type, Richardson balanced		
Maximum travel	inches	6
Outside lap	inches	1 ⅛
Inside lap	inches	0
Ports:		
Length	inches	12.0
Width of steam port	inches	1.5
Width of exhaust port	inches	3.0
Total wheel base	feet	23

Rigid wheel base	feet	8.5
Cylinders:		
Diameter	inches	16
Stroke	inches	24
Drivers, diameter front tire	inches	69.25
Boilers, (style, extended wagon-top:)		
Diameter of front end	inches	52
Number of tubes		200
Gage of tube		12
Diameter of tube	inches	2
Length of tube	feet	11.5
Length of fire-box	inches	72.06
Width of fire-box	inches	34.25
Depth of fire-box	inches	79.00
Heating-surface in fire-box	square feet	126.0
Heating-surface in tubes, water side	square feet	1196.00
Heating-surface in tubes, fire side.	square feet	1086.00
Total heating-surface including water side of tubes	square feet	1322.00
Total heating-surface including fire side of tubes	square feet	1212.00
Total heating-surface, value accepted for use in all calculations	square feet	1322.00
Ratio of total heating-surface based on water side of tubes to that based on fire side of tubes		1.091
Grate area	square feet	17.00
Thickness of crown-sheet	inches	$\frac{7}{16}$
Thickness of tube sheet	inches	$\frac{9}{16}$
Thickness of side and back sheets	inches	$\frac{3}{8}$
Diameter of stay-bolts	inches	1
Diameter of radial stays	inches	1 $\frac{1}{8}$
Driving-axle journals:		
Diameter	inches	7 $\frac{1}{2}$
Length	inches	8 $\frac{1}{2}$

5. *An Alternative for Higher Steam-pressures.*—Previous publications from the Purdue laboratory have shown the possibility under certain conditions of finding a substitute for very high boiler-pressures in the adoption of a boiler of larger capacity, the pressure remaining unchanged. If, for example, in designing a new locomotive, it is found possible to allow an increase of weight in the boiler, as compared with that of some older type of machine, it becomes a question as to whether this possible increase in weight should be utilized by providing for a high-pressure or for an increase in the extent of heating-surface. The results of tests, supplemented by facts concerning the weight of boilers designed for different pressures and for different capacities, supply the data necessary for an analysis of this question. Such an analysis is presented elsewhere. (See Chapters VI and VII.)

II. Difficulties in Operating under High-Pressures

6. *The Work with the Experimental Locomotive* has shown that those difficulties which in locomotive operation are usually ascribed to bad water increase rapidly as the pressure is increased. The water-supply of the Purdue laboratory contains a considerable amount of magnesia and carbonate of lime. When used in boilers carrying low pressure there is no great difficulty in washing out practically all sediment. The boiler of the first experimental locomotive, *Schenectady No. 1*, which carried but 140 lb. and was run at a pressure of 130 lb., after serving in the work of the laboratory for a period of six years, left the testing-plant with a boiler which was practically clean. Throughout its period of service this boiler rarely required the attention of a boiler-maker to keep it tight. Water from the same source was ordinarily used in the boiler of *Schenectady No. 2*, which carried a pressure of 200 lb. or more. It was early found that this boiler operating under the higher pressure frequently required the attention of a boiler-maker. After having been operated for no more than 30,000 miles, cracks developed in the side-sheets, making it impossible to keep the boiler tight, and new side-sheets were applied. In operating under pressures as high as 240 lb., the temperature of the water delivered by the injector was so high that scale was deposited in the check-valve, in the delivery-pipe, and in the delivery-tube of the injector. Under this pressure, with the water normal to the laboratory, the injectors often failed after they had been in action for a period of two hours. The interruptions of tests through failure of the injector, and through the starting of leaks at stay-bolts, as the tests proceeded, became so annoying that, as a last resort, a new source of water supply was found in the return tank of the University heating-plant. This gave practically distilled water, and its use greatly assisted in running the tests at 240 lb. pressure.

Probably some of the difficulties experienced in operating under very high steam-pressures were due to the experimental character of the plant, and would not appear after practice had become committed to the use of such pressures by a gradual process of approach, but the results are clear in their indication that the problem of boiler maintenance, especially in bad-water districts, will become more complicated as pressures are further in

creased. Since, taking the country over, there are few localities where locomotives can be furnished with pure water, the conclusion stated should be accepted as rather far-reaching in its effect.

The tests developed no serious difficulties in the lubrication of valves and pistons under pressures as high as 240 lb., though this could not be done with the grade of oil previously employed.

With increase of pressure any incidental leakage, either of the boiler or from cylinders, becomes more serious in its effect upon performance. In advancing the work of the laboratory, every effort was made to prevent loss from such causes, and tests were frequently thrown out and repeated because of the development of leaks of steam around piston and valve rods, or of water from the boiler. Notwithstanding the care taken, it was impossible under the higher pressures to prevent all leakage, and the best that can be said for the data under these conditions is that they represent results which are as free as practicable from irregularities arising from the causes referred to; that is, as far as leakage may affect performance, the results of the laboratory tests may safely be accepted as a record of maximum performance.

In concluding this brief review of the difficulties encountered in the operation of locomotives under very high steam-pressures, the reader is reminded that an increase of pressure is an embellishment to which each detail in the design of the whole machine must give a proper response. A locomotive which is to operate under such pressure will need to be more carefully designed and more perfectly maintained than a similar locomotive designed for lower pressure; and much of that which is crude and imperfect, but nevertheless serviceable in the operation of locomotives using a lower pressure, must give way to a more perfect practice in the presence of the higher pressure.

III. Boiler Performance

7. *The Performance of the Boiler.*—The pounds of water evaporated per pound of coal plotted in terms of rate of evaporation is shown for each of the several pressures in Fig. 8. The equations representing the performance of the boiler and furnace as established by these lines are:

$E = 11.040 - .221\ H$, when pressure is 240
$E = 11.310 - .221\ H$, when pressure is 220
$E = 11.373 - .221\ H$, when pressure is 200
$E = 11.469 - .221\ H$, when pressure is 160
$E = 11.357 - .221\ H$, when pressure is 120

where E is the number of pounds of water evaporated from and at 212° per pound of coal, and H is the number of pounds of water evaporated from and at 212° per sq. ft. of heating-surface per hour. The area of heating-surface employed is based upon the interior surface of the fire-box and the exterior surface of the tubes. In determining the position of the lines represented by these equations certain conventions were adopted. These, and the reasons underlying them, may be described as follows:

The only difference in the running conditions applying to the tests of each series is that of pressure, and as the terms employed in plotting the several diagrams are the same, it is evident that the differences in performance are only such as may result from the difference in pressure. Since the quantities are in terms of equivalent evaporation, the differences can not be great. Accepting this view, it was first sought to determine the slope of the lines for the several groups. This was done by plotting upon a single sheet all the points, eight in number, available for the series at 240 lb. together with eight points selected as fairly representative from each of the other series, making forty points in all. The result is shown in Fig. 9. Points thus plotted were divided into two groups, one representing the lower rates of combustion, and the other representing the higher rates, the points being so chosen that each group contained four points from each of the several series. The ordinates and abscissæ for points of each group were then determined, and the several values thus obtained averaged. The final results were then plotted, giving the points shown by the circles inclosing a cross (Fig. 9).

The equation from the line drawn through these points is

$$E = 11.305 - 0.221\ H$$

The line thus found (Fig. 9) may fairly be assumed to represent the slope of the mean line of any number of points which for purposes of comparison may be selected from the larger group.

In determining, therefore, the location of the mean lines (Fig. 8), the abscissæ and ordinates of all points were averaged and

the results plotted. Through the derived point a line is drawn having the slope already found; that is, the mean line of Fig. 9.

8. *Effect of Changes in Steam-pressure upon the Evaporative Efficiency of the Boiler.*—The generation of steam at a pressure of 120 lb. involves a temperature of the water which is 50° less than that which must be dealt with in generating steam at a pressure of 240 lb., and in general it has been assumed that any increase in boiler-pressure necessarily results in some loss of evaporative efficiency. It has been known that for the small ranges of pressure common in stationary practice this difference is not great, but the facts have not been established with reference to locomotive performance or for ranges as great as those covered by the experiments under consideration in any service.

The performance of the boiler experimented upon under a range of pressure varying from 240 to 120 lb. may be seen by comparing the mean curves already developed (Fig. 8). This diagram shows that the lowest efficiency is obtained with the highest pressure and that with one exception the lines representing performance under different pressures fall in order, inversely with the pressure. The exception is to be found in the line representing performance at 120 lb. pressure. This line falls low, a condition which may be explained by the fact that the spark and cinder losses for these tests are known to have been excessive. The mean line located from 40 points, representing all pressures (Fig. 9), will represent any of the lines of Fig. 8 with an error not greater than 0.2 lb.

The results clearly define four general facts, which may be stated as follows:

(a). The evaporative efficiency of a locomotive boiler is but slightly affected by changes in pressure.

(b). Changes in steam-pressure between the limits of 120 lb. and 240 lb. will produce an effect upon the efficiency of the boiler which will be less than 0.5 lb. of water per pound of coal.

(c). The equation $E = 11.305 - 0.221\,H$ represents the evaporative efficiency of the boiler of locomotive *Schenectady No. 2* when fired with Youghiogheny coal for all pressures between the limits of 120 lb. and 240 lb. with an average error for any pressure which does not exceed 2.1 per cent.

9. *Smoke-box Temperatures.*—The results of the tests show that in all cases the temperature of the smoke-box gases increases as the rate of evaporation increases. Plotted diagrams showing

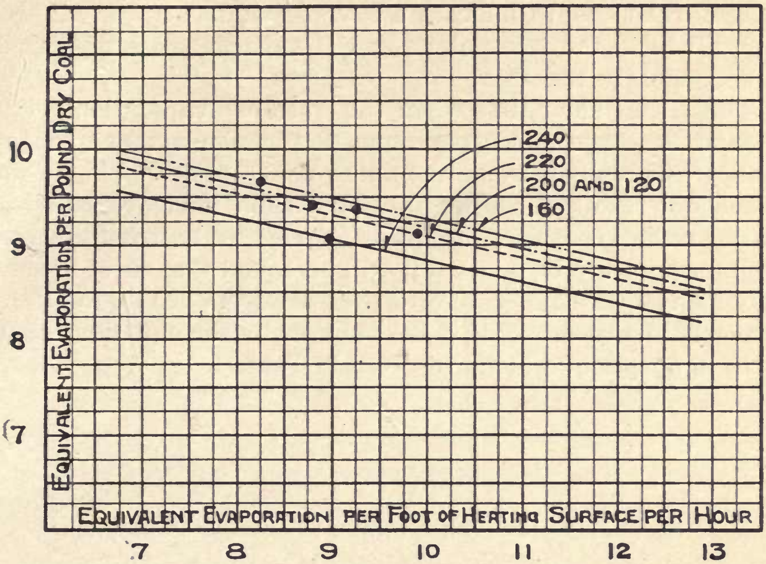

Fig. 8 Evaporation per Pound of Coal under Different Conditions of Pressure

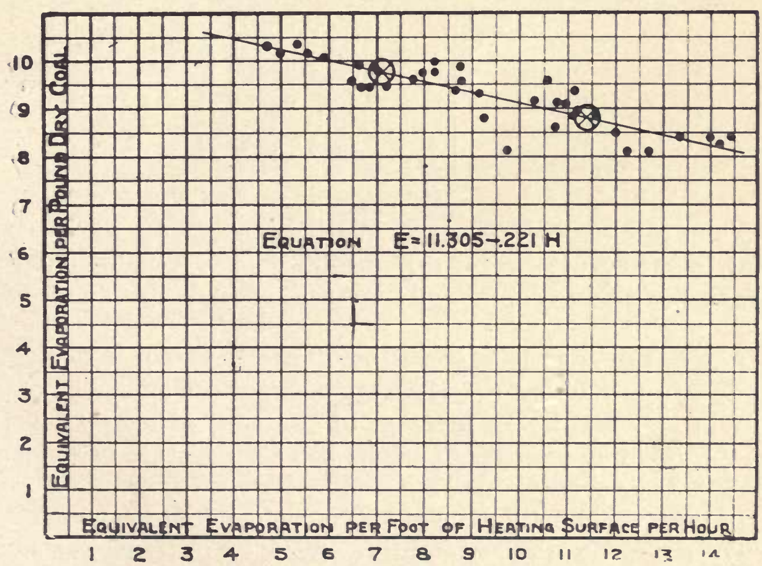

Fig. 9 Evaporation per Pound of Coal under All Conditions of Pressure

the exact relationship indicate a marked similarity for all pressures; all have the same slope and if superimposed they would fall very closely together.

Thus, they show that when the rate of evaporation is 9 lb. per ft. of heating-surface per hour, the smoke-box temperature for all pressures is between the limits of 700° and 730° F. There are but four results for a pressure of 240 lb., in comparison with eight or more for other pressures. If the results from the tests at 240 lb. pressure be omitted it will be found that those remaining, which represent a range of pressure from 220 lb. to 120 lb., are nearly identical. This is best shown by the equations of the curves in question, which are given in Table 1.

TABLE 1

SMOKE-BOX TEMPERATURES UNDER DIFFERENT PRESSURES

Boiler-pressure pounds	Equations
220	$T = 496.3 + 25.66\ H$
200	$T = 491.0 + 25.66\ H$
160	$T = 487.7 + 25.66\ H$
120	$T = 478.9 + 25.66\ H$
Average	$T = 488.5 + 25.66\ H$

The average of the several equations represents the average of any of the several groups of results obtained under different pressures, with an error which in no case exceeds 10° F., or 2 per cent.

Again, the equations show that the effect of increasing the pressure from 120 lb. to 220 lb. is to increase the smoke-box temperature 17°; that is, an increase of pressure of nearly 100 per cent results in an increase of smoke-box temperature of approximately 3.5 per cent.

In the preceding statements is to be found an explanation of the constancy in the evaporative efficiency of the boiler under different steam-pressures. The fact seems to be that the water in the boiler is about as effective in absorbing the heat of the gases

when its temperature is 400° (240 lb. pressure) as when its temperature is but 350° (120 lb. pressure).

The data sustain the following conclusions:

(a). The smoke-box temperature falls between the limits of 590° F. and 850° F., the lower limit agreeing with a rate of evaporation of 4 lb. per ft. of heating-surface per hour and the latter with a rate of evaporation of 14 lb. per ft. of heating-surface per hour.

(b). The smoke-box temperature is so slightly affected by changes in steam-pressure as to make negligible the influence of such changes in pressure for all ordinary ranges.

(c). The equation $T = 488.5 + 25.66\,H$, where T is the temperature of the smoke-box expressed in degrees F., and H is pounds of water evaporated from and at 212° per. ft. of heating-surface per hour, possesses a high degree of accuracy.

10. *Draft.*—The term "draft," as herein employed, represents a reduction of pressure as compared with that of the atmosphere expressed in inches of water. The draft was observed at three different points between the ash-pan and the stack. These were the smoke-box in front of the diaphragm, the smoke-box back of the diaphragm, and the fire-box. At each of these points connection was made with a U-tube containing water. The results for each different steam-pressure vary but little so that those representing the draft as affected by rate of evaporation for any one pressure, for example, 160 (Fig. 10), are fairly representative of the entire exhibit. Referring to Fig. 10, the solid points represent the draft in the smoke-box in front of the diaphragm; the crosses, the draft behind the diaphragm; and the circles, the draft in the fire-box. Expressing the results in other terms, it appears that vertical distances between the highest curve and the intermediate represent the resistance of the diaphragm; vertical distances between the intermediate and the lowest curve, the resistance of the tubes; and vertical distances between the lowest curve and the axis, the resistance of the ash pan, the grate, and the fire upon it. Values under this curve are a close approach to the effective draft. In general, draft values vary greatly with the conditions at the grate. A thin, clean fire results in comparatively low draft values throughout the system, while a thick fire, or one which is choked by clinkers, leads to the reverse re-

sults. It is for this reason that individual points representing draft sometimes vary widely from the mean of all results.

When the rate of evaporation is 10 lb. per ft. of heating-surface per hour, the draft in front of the diaphragm is approximately 4 inches for all pressures.

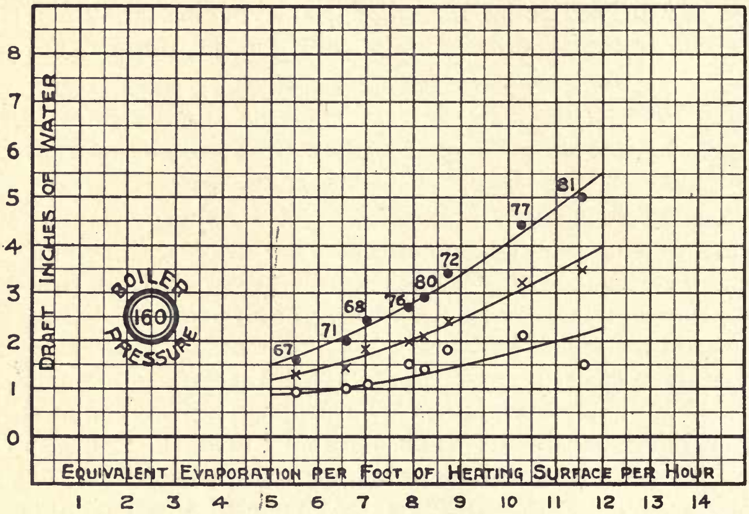

FIG. 10 DRAFT

11. *Composition of Smoke-box Gases.*—As previous experiments had shown irregularities in the evaporative efficiency of boilers of locomotives, it was early decided to proceed with care in determining the composition of the smoke-box gases. It seemed probable that if the composition of these were known for each test, variations in the evaporative efficiency of the boiler might be explained. To this end, therefore, each step in the process was carefully considered, and the work of sampling and analyzing the gases was assigned to a chemist of experience who had no other duties to perform.

The gases were drawn from the smoke-box over mercury, a period of from a half hour to an hour and a half being employed in securing the sample. The sampling-tube was of copper and of small diameter. Its length was sufficient to extend to the center of the smoke-box, and gas was admitted to it by small perforations at the extreme end only. This tube could be drawn in

and out through a stuffing-box to permit the sample to be taken either from the center of the smoke-box or from any location between that point and the shell. In securing the sample it was the practice to move the tube systematically at regular intervals of time. By these means it was assumed that abnormal results due to fluctuations in the condition of the fire would be entirely avoided.

The results, notwithstanding all precautions, have not proved entirely satisfactory; that is, where the evaporative performance is abnormal, they do not permit the assignment of a definite cause. The defects are doubtless due to faulty sampling, though it is not clear in what manner the sampling may be improved in connection with locomotive work. They do, however, entirely justify certain general conclusions. They show that the amount of excess air admitted to the furnace is never great, and in most cases it is very small—far below the limits which are thought desirable in stationary practice. They show, also, that the excess air diminishes as the rate of combustion increases. It is apparent, therefore, that the loss in efficiency arising from excess air is under normal conditions smaller than in most other classes of service. Moreover, while the supply of air appears limited, it is significant that the losses from imperfect combustion, as shown by the presence of CO, are also small, the actual amount varying irregularly between limits which are very narrow.

12. *The quality of steam* was uniformly high under all conditions for pressure, the average for all tests being 99.08. The quality declined slightly with increase of pressure, but in no case did the moisture exceed 1.35 per cent.

IV. Engine Performance

13. *Mean Effective Pressure.*—A review of the calculated results shows that the possible range of cut-off under a fully-open throttle is reduced by a definite amount with each increment of pressure. For example, under 120 lb. pressure, it is possible to operate at 30 miles per hour with the reverse lever in the fourteenth notch from the center, while at 240 lb. the longest cut-off under similar conditions of speed is represented by the

fourth notch of the reverse lever. It is of interest to note, also, that within the range of the experiments each change in the position of the reverse lever results in a change in power which is nearly proportional to the extent of the movement of the reverse lever.

14. *The Indicated Horse-power.*—The range in the values of the indicated horse-power for all pressures falls between the limits of 134 and 610 horse-power. It appears from the results that with the coal used during the tests the normal power of the locomotive tested, when run at speed, is between 450 and 500 horse-power. The development of more than 500 horse-power was always attended by unusual efforts on the part of the fireman. The power of the engine, under a pressure of 240 lb., was readily developed with the reverse lever in the second and fourth notches, while under 120 lb. pressure either a high speed or a much longer cut-off must be employed before this condition is reached. All this, of course, grows out of the fact that in experiments involving a wide range of pressure the cylinder volume remained constant. It is significant that the only two tests giving a horse-power in excess of 600 lb. were run at 180 lb. and 200 lb., respectively. It will hereafter be shown that the operation of the engine under these pressures was more efficient than under conditions of pressure which were either lower or higher. Remembering that the results disclose the entire range for which it was practicable to operate the engine under a fully-open throttle, it will be accepted as a noteworthy fact that the higher pressures do not serve to increase the output of power.

15. *Steam per Indicated Horse-power per Hour.*—The high efficiency which is implied by results showing the steam consumption per indicated horse-power per hour, and the narrow range which they represent, taken in connection with the comprehensive character of the running conditions involved, are matters of more than ordinary importance. For example, at a pressure of 240 lb., the engine experimented upon, when working under a fully-open throttle, gave a horse-power hour in return for the consumption of less than 24 lb. of steam, and under any condition of speed or cut-off for which it was found possible to operate the engine under a wide-open throttle, the consumption never exceeded 26.3 lb. At lower pressures, involving the possibility of a wider choice in the conditions of operating, the range is somewhat

increased. Thus, at 120 lb. pressure the minimum value is 27.5 and the maximum 33.8, a range which, while greater than that just referred to, is nevertheless extremely narrow as compared with the range incident to the operation of other classes of engines.

The most efficient point of cut-off for the lowest pressure is that secured when the reverse lever is in the eighth notch, which is equal to 35 per cent of the stroke. At 200 lb. pressure the most efficient cut-off is that represented by the sixth notch, or 27 per cent of the stroke, and the data do not disclose that a shorter cut-off than this under a fully-open throttle is profitable for the engine experimented upon, even though the pressures be raised to 240 lb. In all cases the best results are obtained at a speed either of 20 or 40 miles an hour; for all pressures above 160 lb., the most efficient speed is 40 miles. The law of the change of efficiency with changes in speed has been discussed and the reasons underlying pointed out elsewhere.[1]

The least steam consumption for each speed under the several different pressures employed is set forth in Fig. 11. The values of the figure are of interest. They do not, however, constitute a satisfactory base upon which to form comparisons.

Speed-Miles per Hour	120	160	180	200	220	240
50	28.12	26.12	24.43	25.74	24.08	24.97
40	27.51	25.82	23.68	24.43	23.68	23.86
30	27.46	25.28	24.61	24.91	23.59	24.43
20	28.40	26.14	25.44	26.01	25.51	24.09
Average	27.87	25.84	24.54	25.27	24.21	24.34

Boiler Pressure

FIG. 11 LEAST STEAM FOR EACH OF THE SEVERAL SPEEDS AT DIFFERENT PRESSURES

16. *Steam Consumption under Different Pressures.*—The shaded zone upon Fig. 12 represents the range of performance as it appears from all tests run under the several pressures employed.

[1] Locomotive Performance, published by John Wiley & Sons.

For purposes of comparison, it is desirable to define the effect of pressure on performance by a line, and to this end an attempt has been made to reduce the zone of performance to a representative line. In preparing to draw such a line, the average performance of all tests at each of the different pressures was obtained and plotted, the results being shown by the circles in Fig. 12. Points thus obtained can be regarded as fairly representing the performance of the engine under the several pressures only so far as the tests run for each different pressure may be assumed to fairly represent the range of speed and cut-off under which the engine would ordinarily operate. The best result for each different pressure, as obtained by averaging the best results for each speed at constant pressure, is given upon the diagram in the form of a light cross. These points may be regarded as furnishing a satisfactory basis of comparison in so far as it may be assumed that when the speed has been determined, an engine in service will always operate under conditions of highest efficiency. Again, the left-hand edge of the shaded zone represents a comparison based on maximum performance at whatever speed or cut-off. In addition to the points already described, there is located upon the diagram (Fig. 12) a curve showing the performance of a perfect engine,[1] with which the plotted points derived from the data of tests may be compared. Guided by this curve representing the performance of a perfect engine, a line, *AB*, has been drawn proportional thereto, and so placed as to fairly represent the circular points derived from the experiments. It is proposed to accept this line as representing the steam consumption of the experimental engine under the several pressures employed. It is to be noted that it is not the minimum performance nor the maximum, but it is a close approach to that performance which is suggested by an average of all results derived from all tests which were run. Since its form is based upon a curve of perfect performance, it has a logical basis, and since it does no violence to the experimental data, its use seems justifiable.

17. *Performance under Different Pressures, A Logical Basis for Comparison.*—The record of boiler performance as set forth in

[1] This curve represents the performance of an engine working on Carnot's cycle, the initial temperature being that of steam at the several pressures stated, and the final temperature being that of steam at 1.3 lb. above atmospheric pressure. This latter value is the assumed pressure of exhaust in locomotive service.

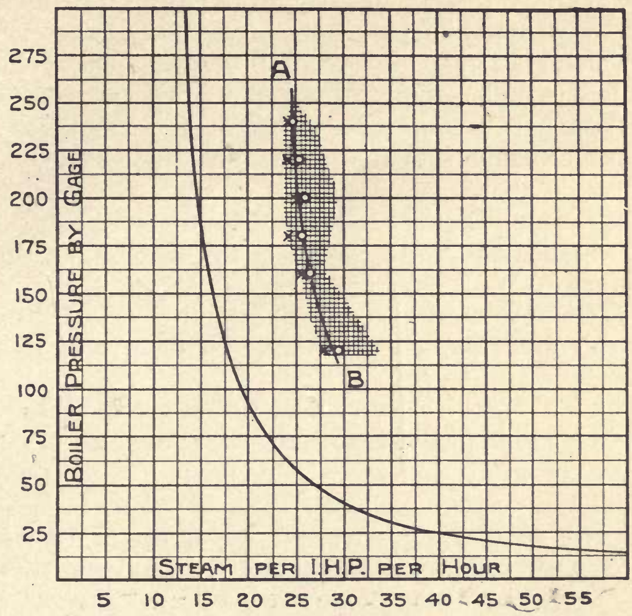

FIG. 12 STEAM CONSUMPTION UNDER DIFFERENT PRESSURES

Chapter III, is that actually obtained from the several tests run. It has already been shown that this performance is affected by variations in the evaporative efficiency of the boiler, due doubtless to irregularities in firing, but which are in fact unaccounted for. One of the purposes of the discussion which occupies the preceding chapter has been to reduce the values actually resulting from the tests to a summarized statement which may be accepted as a general definition of performance, assuming all irregularities to have been eliminated. Such a summarized statement is that which is shown by Fig. 9. It is also expressed by the equation

$$E = 11.305 - 0.221\ H$$

It is now proposed to determine the coal consumption per indicated horse-power, assuming the boiler efficiency to have been in all cases that which is expressed by this equation.

It appears, also, from the data that the steam consumed by the cylinders varies for each different pressure with changes in speed and cut-off, and it has been sought in the preceding para-

graphs to summarize the facts derived from the experiments into a single expression. This appears in the form of the curve *AB*, Fig. 12, which is to be accepted as representing the performance of the cylinders under different pressures without reference to speed or cut-off. Combining this general statement expressing cylinder performance with that already obtained covering boiler performance, it should be possible to secure an accurate measure of the coal consumption per indicated horse-power hour, for each different pressure which will represent the results of all tests at that pressure.

The steps in this process are set forth by Table 2, in which—

Column 1 gives the several pressures embraced by the experiments.

Column 2 gives the steam consumption per indicated horse-power hour for each of these several pressures as taken from the curve *AB*, Fig. 12.

Column 3 gives the number of thermal units in each lb. of steam at the several pressures assuming the feed-water in all cases to have had a temperature of 60° F. The values of this column show at a glance the rate of change in the amount of heat required to supply steam at the different pressures embraced by the experiments.

Column 4 gives the pounds of water from and at 212° F. per indicated horse-power hour. It equals Column 2 × Column 3 ÷ 965.8.

Column 5 gives the pounds of water evaporated from and at 212° F. per pound of coal and is calculated as follows: Assuming that a fair average load for the locomotive tests is 440 horse-power, and that this unit of power is delivered under all pressures, the corresponding rate of evaporation may be found by multiplying this value by those of Column 4 and dividing by the area of heating-surface; that is, the rate of evaporation = 440 × Column 4 ÷ 1322. The equivalent pounds of water per pound of coal is found by substituting the rates of evaporation found for H in the equation,

$$E = 11.305 - 0.221\ H.$$

Column 6 gives the pounds of coal per indicated horse-power per hour and equals Column 4 ÷ Column 5.

Column 7 gives the pounds of coal saved per horse-power hour for each 20-lb. increment in steam-pressure.

Column 8 gives the percentage saving in coal for each 20-lb. increment in steam-pressure.

TABLE 2

Engine Performance under Different Pressures

Boiler Pressure	Steam per Indicated Horse-power per Hour. Values from Curve	B.t.u. Given to 1 Pound Steam Feed-water Temp.=60. °	Equivalent Pounds of Water per Indicated Horse-power Hour	Equivalent Pounds of Water per Pound of Dry Coal	Pounds of Coal per Indicated Horse-power Hour	Coal Saving for Each Increment	
						Lb.	Per cent
1	2	3	4	5	6	7	8
240	24.7	1176.6	30.09	9.10	3.31	.06	1.8
220	25.1	1174.4	30.52	9.06	3.37	.06	1.8
200	25.5	1172.0	30.94	9.03	3.43	.07	2.0
180	26.0	1169.5	31.48	8.99	3.50	.09	2.5
160	26.6	1166.8	32.14	8.94	3.59	.18	4.8
140	27.7	1163.8	33.38	8.85	3.77	.23	5.8
120	29.1	1160.5	34.97	8.73	4.00	...	...

The values of Table 2, especially those of Columns 2 and 6, are of more than ordinary significance. They represent logical conclusions based upon the results of all tests. Comparisons between them will show the extent to which the performance of a locomotive will be modified by changes in the steam-pressure under which it is operated. They show in the matter of steam consumption (Column 2) that—

Increasing pressure from 160 to 180 lb. reduces the steam consumption 0.6 lb. or 2.3 per cent.

Increasing pressure from 180 to 200 lb. reduces the steam consumption 0.5 lb. or 1.9 per cent.

Increasing pressure from 200 to 220 lb. reduces the steam consumption 0.4 lb. or 1.6 per cent.

Increasing pressure from 220 to 240 lb. reduces the steam consumption 0.4 lb. or 1.6 per cent.

In the matter of coal consumption (Column 6) they show that—

Increasing pressure from 160 to 180 lb. reduces the coal consumption 0.9 lb. or 2.5 per cent.

Increasing pressure from 180 to 200 lb. reduces the coal consumption 0.7 lb. or 2.0 per cent.

Increasing pressure from 200 to 220 lb. reduces the coal consumption 0.6 lb. or 1.8 per cent.

Increasing pressure from 220 to 240 lb. reduces the coal consumption 0.6 lb. or 1.8 per cent.

These values are from actual tests. Those who are inclined to insist upon basing their conclusions upon observed data will perhaps find in them a satisfactory conclusion of the whole investigation. The results show how slight is the gain to be derived from any increment of pressure when the basis of the increments is above 160 lb. But they do not in fact tell the whole story. In order to secure such results from a single locomotive it was necessary to employ a machine designed for the highest pressure experimented upon. Obviously, for the tests at lower pressure, the locomotive was needlessly heavy for its dimensions. If, for the tests under each of the lower pressures, the excess weight could have been utilized in providing a boiler of greater heating-surface, the difference in performance with each increment of pressure would have been less than that to which attention has already been called. It is for this reason that the results already quoted, while significant and concise in their meaning, are nevertheless to be accepted as insufficient when regarded as a relative measure of the value of different steam-pressures. An extension of the discussion leading to a more general view of the matter will be found set forth in Chapters VI to VIII.

V. Machine Friction and Performance at Draw-Bar

18. *The Cylinders vs. the Draw-Bar as a Base from Which to Estimate Performance.*—In the latter paragraphs of the preceding chapter results are given disclosing the performance of boiler and engine as based upon cylinder performance. This is a correct basis from which to proceed in discussing the relative advantage of different steam-pressures; for the process of the cylinders represents the last of the thermodynamic changes by which the heat of the fuel is transformed into work. The cylinders are in fact one step nearer the problem in question than the draw-bar, which for many purposes is properly regarded as a better basis from which to determine the performance of a locomotive. This being the case, the purpose of the present chapter will be entirely served if attention is called to a few of the more significant facts which center in the output of power at the draw-bar, leaving the

general discussion as to the relative values of different steam-pressures to be continued in the chapters which follow.

19. *Machine Friction.*—This is the difference between work done in the engine cylinders and that which appears at the draw-bar. It is difficult to summarize the facts concerning engine friction. This is not due to defects in the experimental process underlying the data, but to the fact that the frictional resistance of the machinery of the locomotive varies greatly from day to day.[1] Evidence of this is accessible even to the casual observer. During any given test it is likely that an axle-box or a crank-pin may run warm, while during another test under identical conditions of power the same part will remain perfectly cool. For this reason many variations in the frictional resistance of the machine occur. It is a fact, however, that the friction varies but slightly with increase in steam-pressure, and that changes in cut-off are most effective in modifying engine friction. Acting upon this suggestion, all results have been plotted in terms of cut-off. The results do not, of course, fall in line, but they take such positions as readily to suggest the form of a curve which in an approximate way may be employed to represent them. From such a curve the values set forth in Fig. 13 have been derived. It is proposed to accept

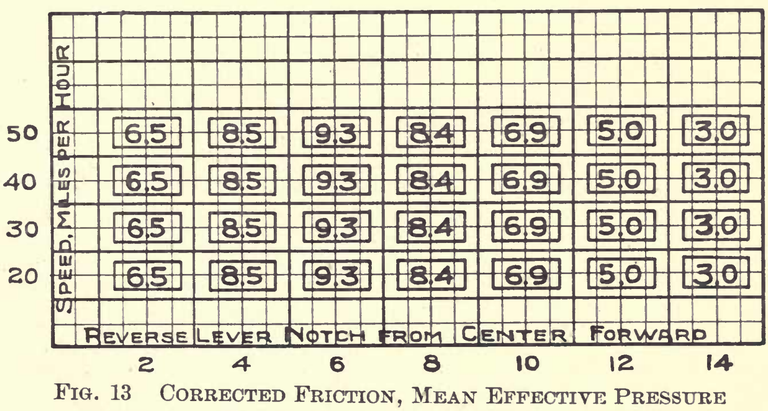

FIG. 13 CORRECTED FRICTION, MEAN EFFECTIVE PRESSURE APPLICABLE TO ALL PRESSURES

these values as an approximate measure of the frictional loss for locomotive *Schenectady No. 2* under all pressures. They are probably a little low for pressures above 200 lb. and are perhaps

[1] A general discussion of this question with data will be found in Locomotive Performance.

somewhat high for pressures below this limit. It can not be assumed that they apply to any other locomotive than that which was involved by the experiments. The machine friction as expressed in pounds pull at the draw-bar may be found for any test by multiplying the mean effective pressure for that test by the constant 88.75.

20. *Steam per Dynamometer Horse-power per Hour.*—Values covering this factor express the combined efficiency of the cylinders and machinery of the locomotive. They disclose the fact that there are few conditions of running for which the locomotive requires more than 30 lb. of steam per dynamometer horse-power hour, and the consumption may fall below 27 lb. While differences in performance for all pressures above 200 lb. are not great, the steam consumption is much greater when the pressure is as low as 120 lb. The data show, also, that for best results the cut-off must be lengthened as the pressure is decreased. The facts as disclosed by the data are as follows:

For 240 lb. pressure the best cut-off is approximately the second notch, 14 per cent.

For 220 lb. pressure the best cut-off is approximately the fourth notch, 19 per cent.

For 180 lb. pressure the best cut-off is approximately the eighth notch, 33 per cent.

For 120 lb. pressure the best cut-off is approximately the twelfth or fourteenth notch, 47 per cent or 56 per cent.

21. *Coal per Dynamometer Horse-power per Hour.*—This factor represents the combined performance of the boiler, the cylinders, and the machinery of a locomotive. It connects the energy developed in the boiler by the combustion of fuel with that which is developed at the draw-bar. In all cases where data are given, the fuel consumed was of the same quality; hence all results are comparable. Under a pressure of 240 lb. the range is between 3.35 and 5.01, while at a pressure of 160 lb. the range is between 3.79 and 4.78, results which are of interest from at least two points of view: first, because of the small difference in performances resulting from a relatively large change in pressure; and second, because of the significance of the values quoted when accepted as a measure of the locomotive performance. It is doubtful if any other type of steam-engine exhausting into the atmosphere can

be depended upon to deliver power from the periphery of its wheel in return for the expenditure of so small an amount of fuel.

22. *Corrected Results.*—The values representing coal and steam consumption which have thus far been referred to as performance at the draw-bar are those actually observed. A close comparison of these sometimes fails to give consistent results because of irregularities in boiler performance or in the frictional resistance of the machinery growing out of causes already discussed.

In Table 3 values are presented from which all such discrepancies have been eliminated. They are those which would have been obtained if the evaporative efficiency for all tests had been that indicated by the equation:

$$E = 11.305 - 0.221\,H$$

and if the machine friction for all cases had been that shown by Fig. 13. Column 13 giving the corrected coal per dynamometer horse-power, and Column 14 the corrected steam per dynamometer horse-power, may be accepted as representing the best information derived from the entire research.

TABLE 3

COMPARATIVE PERFORMANCE OF THE LOCOMOTIVE, ASSUMING IRREGULARITIES IN THE RESULTS OF INDIVIDUAL TESTS TO HAVE BEEN ELIMINATED

Number	Designation of Tests Laboratory Symbol	Equivalent Steam to Engine per Hour. Feed-water at 60° F.	Equiv. Evap. per Pound of Dry Coal by Equation $E = 11.305 - .221\,H$	Dry Coal Fired per Hour Corrected by Equation, pounds	Dry Coal per I. H. P. per Hour, pounds	Equiv. Steam per I. H. P. per Hour, pounds	Machine Friction M. E. P.	Machine Friction H. P.	Machine Friction Per cent I. H. P.	Dynamometer Horse-power	Draw-bar Pull pounds	Coal per D. H. P. per Hour, pounds	Equiv. Steam per D. H. P. per Hour pounds
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	20–2–240	8803	9.835	895	3.24	31.84	6.5	30.8	11.1	245.6	4600	3.64	35.86
2	20–4–240	12008	9.298	1291	3.29	30.59	8.5	40.2	10.2	352.3	6610	3.66	34.08
3	20–6–240	13614	9.029	1508	3.23	29.12	9.3	44.0	9.4	422.8	7930	3.56	32.20
5	30–2–240	11444	9.392	1218	3.28	30.82	6.5	46.1	12.4	325.2	4060	3.74	35.19
6	30–4–240	13888	8.983	1546	3.28	29.51	8.5	60.4	12.8	410.2	5127	3.77	33.85
8	40–2–240	12320	9.245	1333	3.16	29.20	6.5	61.5	14.6	360.3	3379	3.69	34.19
9	40–4–240	16320	8.576	1903	3.36	28.82	8.5	80.5	14.2	485.8	4550	3.91	33.59
11	50–2–240	14066	8.953	1571	3.37	30.21	6.5	76.9	16.5	388.6	2910	4.04	36.19
13	20–2–220	8533	9.878	864	3.38	33.42	6.5	30.8	12.0	224.5	4210	3.84	38.01
14	20–4–220	10681	9.519	1122	3.27	31.15	8.5	40.2	11.7	302.6	5670	3.71	35.29
15	20–6–220	13294	9.082	1463	3.39	30.81	9.3	44.0	10.2	387.4	7260	3.77	34.31
16	20–8–220	16653	8.521	1954	3.66	31.24	8.4	39.8	7.5	493.2	9250	3.96	33.76
17	30–2–220	10286	9.585	1073	3.35	32.11	6.5	46.1	14.4	274.2	3430	3.91	37.51
18	30–4–220	12976	9.136	1420	3.20	29.06	8.5	60.4	13.5	386.1	4820	3.68	33.60
19	30–6–220	15915	8.644	1841	3.29	28.44	9.3	66.0	11.8	493.5	6170	3.73	32.25
21	40–2–220	11471	9.387	1222	3.29	30.87	6.5	61.5	16.5	310.0	2910	3.94	37.00
22	40–4–220	14549	8.873	1638	3.21	28.57	8.5	80.5	15.8	428.6	4020	3.82	33.94
24	50–2–220	12017	9.296	1292	3.41	31.72	6.5	76.9	20.3	301.9	2260	4.28	39.80
25	50–4–220	16343	8.573	1906	3.39	29.08	8.5	100.6	17.9	461.7	3460	4.13	35.40
29	20–2–200	7632	10.029	761	3.40	34.14	6.5	30.8	13.8	192.7	3610	3.94	39.61
30	20–4–200	9100	9.784	930	3.23	31.64	8.5	40.2	14.0	247.4	4640	3.75	36.78
31	20-6–200	11774	9.337	1261	3.35	31.33	9.3	44.0	11.7	331.8	6220	3.80	35.48
32	20–8–200	15011	8.795	1707	3.60	31.74	8.4	39.8	8.4	433.1	8120	3.94	34.66
33	30–2–200	8768	9.839	891	3.31	32.60	6.5	46.1	17.1	222.8	2780	4.00	39.35
34	30–4–200	11354	9.406	1207	3.29	30.92	8.5	60.4	16.4	306.7	3830	3.93	37.02
35	30–6–200	14685	8.850	1659	3.39	30.00	9.3	66.0	13.5	423.2	5290	3.92	34.70
37	40–2–200	9934	9.644	1030	3.36	32.40	6.5	61.5	20.0	245.1	3300	4.22	40.53
38	40–4–200	13361	9.071	1473	3.28	29.76	9.5	80.5	17.9	368.4	3450	4.00	36.27
39	40–6–200	17822	8.321	2142	3.54	29.54	9.3	88.0	14.5	517.2	4850	4.14	34.46
41	50–2–200	10206	9.599	1074	3.26	31.02	6.5	76.9	23.4	252.1	1890	4.26	40.48
42	50–4–200	14431	8.892	1623	3.49	31.08	8.5	100.6	1.6	363.6	2730	4.46	39.69
46	20–2–180	6638	10.195	651	3.40	34.57	6.5	30.8	16.0	161.2	3020	4.04	41.18
47	20–4–180	8475	9.888	858	3.25	32.15	8.5	40.2	15.3	223.4	4190	3.84	37.94

TABLE 3 (Continued)

Number	Description of Tests / Laboratory Symbol	Equivalent Steam to Engine per Hour, Feed-water at 60° F.	Equiv. Evap. per Pound of Dry Coal by Equation $E = 11.305 - .221\ H.$	Dry Coal Fired per Hour Corrected by Equation, pounds	Dry Coal per I. H. P. per Hour, pounds	Equiv. Steam per I. H. P. per Hour, pounds	Machine Friction			Dynamometer Horse-power	Draw-bar Pull, pounds	Coal per D. H. P. per Hour, pounds	Equiv. Steam per D. H. P. per Hour, pounds
							M. E. P.	H. P.	Per cent I.H.P				
1	2	3	4	5	6	7	8	9	10	11	12	13	14
48	20–6–180	10226	9.595	1066	3.19	30.61	9.3	44.0	13.2	290.1	5440	3.67	35.25
49	20–8–180	12833	9.157	1401	3.40	31.17	8.4	39.8	9.7	371.9	6970	3.77	34.51
51	30–2–180	7523	10.047	749	3.18	31.91	6.5	46.1	19.5	189.6	2370	3.95	39.68
52	30–4–180	9722	9.680	1004	3.16	30.65	8.5	60.4	19.1	256.7	3210	3.91	37.87
53	30–6–180	11633	9.360	1243	3.16	29.58	9.3	66.0	16.8	327.3	4090	3.80	35.54
54	30–8–180	16156	8.604	1878	3.44	29.57	8.4	59.6	10.9	486.7	6080	3.86	33.20
56	40–2–180	8069	9.956	810	3.12	31.14	6.5	161.5	23.7	197.6	1850	4.10	40.84
57	40–4–180	11177	9.436	1184	3.07	28.94	8.5	80.5	20.8	305.7	2870	3.87	36.56
58	40–6–180	14907	8.813	1691	3.23	28.44	9.3	88.0	16.8	436.1	4090	3.88	34.18
59	40–8–180	18949	8.137	2329	3.82	31.07	8.4	79.5	13.0	530.4	4970	4.39	35.73
61	50–2–180	8578	9.871	869	3.24	32.01	6.5	76.9	28.7	191.1	1430	4.55	44.88
62	50–4–180	12061	9.288	1299	3.16	29.37	8.5	100.6	24.5	310.0	2320	4.19	38.90
63	50–6–180	16567	8.535	1941	3.51	29.94	9.3	110.1	19.9	443.2	2320	4.38	37.40
67	20–4–160	7396	10.068	734	3.34	33.69	8.5	40.2	18.4	179.3	3360	4.09	41.25
68	20–6–160	9379	9.737	963	3.27	31.87	9.3	44.0	14.9	250.4	4690	3.85	37.44
69	20–8–160	11392	9.400	1212	3.51	33.02	8.4	39.8	11.5	305.2	5720	3.97	37.33
71	30–4–160	8785	9.836	893	3.28	32.28	8.5	60.4	22.2	211.7	2640	4.22	41.50
72	30–6–160	11663	9.355	1246	3.25	30.38	9.3	66.0	17.2	317.9	3970	3.92	36.69
73	30–8–160	14347	8.906	1611	3.46	30.85	8.4	59.6	12.8	405.4	5070	3.97	35.39
76	40–4–160	10106	9.615	1051	3.31	31.83	8.5	80.5	25.4	237.0	2220	4.43	42.64
77	40–6–160	13406	9.065	1478	3.43	31.05	9.3	88.0	20.4	343.7	3220	4.30	39.00
78	40–8–160	17246	8.421	2048	3.76	31.70	8.4	79.5	14.6	464.4	4350	4.41	37.14
80	50–4–160	10982	9.469	1160	3.43	32.47	8.5	100.6	29.7	237.7	1773	4.89	46.20
81	50–6–160	14940	8.807	1696	3.56	31.39	9.3	110.1	23.1	365.8	2740	4.64	40.84
85	20–4–120	5215	10.433	500	3.73	38.92	8.5	40.2	30.0	93.8	1760	5.33	55.59
86	20–8–120	8592	9.869	871	3.44	33.99	8.4	39.8	15.7	213.0	3990	4.09	40.34
87	20–12–120	12329	9.244	1333	3.73	34.52	5.0	23.7	6.5	333.2	6250	4.00	37.00
88	30–4–120	6269	10.257	611	3.57	36.69	8.5	60.4	35.4	110.6	1380	5.52	56.68
89	30–8–120	10683	9.519	1122	3.45	32.80	8.4	59.6	18.3	265.9	3320	4.22	40.18
90	30–14–120	18654	8.186	2278	4.43	36.29	3.0	21.3	4.1	492.7	6160	4.62	37.86
91	40–4–120	6649	10.193	652	3.54	36.13	8.5	80.5	43.7	103.5	970	6.30	64.24
92	40–8–120	12796	9.166	1396	3.59	32.89	8.4	79.5	20.4	309.5	2900	4.51	41.34
93	40–12–120	18942	8.138	2328	4.20	34.12	5.0	47.3	8.5	507.5	4760	4.58	37.32
94	50–4–120	7129	10.113	704	4.00	40.51	8.5	100.6	57.2	75.4	560	9.34	94.55
95	50–8–120	14371	8.902	1614	3.77	33.61	8.4	99.4	23.2	328.2	2460	4.91	43.79
96	50–11–120	19317	8.075	2391	4.32	34.90	6.0	71.0	12.8	482.5	3620	4.95	40.04

VI. Boiler Pressure As a Factor in Economical Operation

23. *The amount of steam consumed* by the locomotive per unit power developed, when operated under various pressures between the limits of 120 lb. and 240 lb., has already been defined (Fig. 12). Basing conclusions on results thus disclosed, it is now proposed to determine the increase in efficiency which may be secured through the adoption of higher pressure for any given increase in the weight of the boiler and its related parts. That this may be done, it is essential to determine the relation between boilers of a given size when designed for different pressures.

24. *Weight of Locomotive as Affected by Steam-Pressure.*—The parts of a locomotive which are affected by changes in steam-pressure, assuming the power to remain constant, are the boiler and certain portions of the engine. The boiler to be adapted to a higher steam-pressure requires thicker plates, heavier riveting, and stronger staying, all tending to augment its weight. The effect of the change upon the engine, however, is to make it lighter, for since with increased pressure, cylinders, pistons, and valves become smaller, their weight will generally diminish. As a basis for exact values, defining their relationship, lines were laid down for a boiler of the following dimensions:[1]

Diameter of first ring	inches	63
Number of 2-inch tubes		258
Length of tubes	feet	14
Total heating-surface	square feet	2024
Length of grate	inches	90
Width of grate	inches	60
Area of grate	feet	37.5
Boiler-pressure	pounds	190

Four designs were made, adapted to four different pressures, respectively, from which designs weights were calculated, with results shown by Table 4.

The weight of the cylinders, valves, and pistons which would be used with a boiler having 2024 sq. ft. of heating-surface in making up a representative locomotive carrying the different pressures designated is set forth in Column 3. The weight of water when the boiler is filled to the second gage appears as Column 4. The weight of steam is negligible. The total weight of all parts

[1] These and other determinations involve weights of boilers which were supplied by the courtesy of the American Locomotive Company.

TABLE 4

WEIGHT OF THOSE PARTS OF A LOCOMOTIVE WHICH ARE AFFECTED BY CHANGES IN BOILER PRESSURE

Boiler Pressure	Weight of Boiler pounds	Weight of Cylinders, Valves, and Pistons pounds	Weight of Water pounds	Weight of All Parts Affected by Changes in Pressure pounds
1	2	3	4	5
160	30679	12580	16349	59608
190	32913	12240	16536	61689
220	36076	11990	16661	64727
250	38953	11620	16848	67421

of the locomotive directly affected by the changes in pressure is given in Column 5, and the values of this column, for the purpose of interpolation, have been plotted in terms of steam-pressure, with results as set forth by Fig. 14.

With these data it is proposed to show the extent to which the performance of a typical locomotive using saturated steam may be improved by increasing the pressure carried within its boiler. For convenience, six different pressures having values between 120 lb. and 220 lb. will be utilized as bases from which to

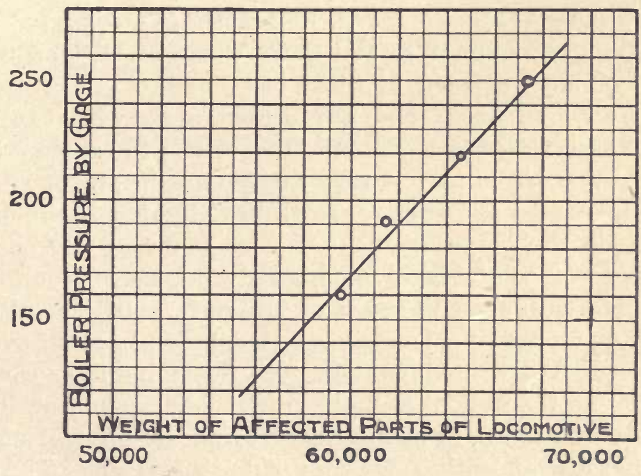

FIG. 14 WEIGHT OF BOILER AS AFFECTED BY CHANGES IN PRESSURE

assume an increase of pressure. The increase of pressure from each base will be such as may be possible upon the allowance of definite increments in the weight of those portions of the locomotive affected by pressure, and in like manner the improvement in performance will be expressed as a per cent of that which is normal to the base. The results of the process outlined are presented in Table 5. An explanation of the columns of this table whose meaning is not self-evident follows:

Column 3. Weight of those parts of a typical locomotive affected by changes in steam-pressure, including water in boiler.—The values of this column, for each of the several pressures stated in Column 2, are taken directly from the diagram of Fig. 14, the basis of which has already been explained.

Column 5. New boiler-pressure obtainable by utilizing the increase of weight in making a stronger boiler.—The values in this column for each of the several weights stated in Column 4 were taken from the diagram in Fig. 14.

Column 6. Steam per indicated horse-power per hour at the pressures given in Column 2.—Values for this column are taken directly from the curve of Fig. 12.

Column 7. Steam per indicated horse-power per hour at the new pressures given in Column 5.—These values, also, were taken directly from the diagram (Fig. 12).

Column 8. Direct saving in steam consumption, resulting from an increased weight equal to the per cent shown in Column 1.—Values of this column are equal to 100 times those of Column 6 minus those of Column 7 divided by those of Column 6.

Column 9. Indirect saving due to reduced rates of evaporation, per cent.—Assuming the locomotive to work at the same power at whatever pressure it may carry, the saving in steam resulting from the increased pressure set forth in Column 8 diminishes the demand upon the boiler, and, as the efficiency of the boiler increases as the rate of evaporation is reduced, there results an indirect saving with each increase of pressure. The relation between the evaporative efficiency of the boiler and rate of evaporation has already been defined (Fig. 9). Assuming the normal rate of evaporation for the boiler under initial conditions to be 10, then a reduction of 1 per cent in the rate of evaporation will effect an increase in the evaporative efficiency of 0.243 per cent. The values in Column 9, therefore, are those of Column 8 multiplied by the constant 0.243.

TABLE 5

TOTAL SAVING WHEN A POSSIBLE INCREASE OF WEIGHT IS UTILIZED AS A MEANS OF INCREASING BOILER-PRESSURE

Increase of Weight per cent	Boiler-pressures Selected as Bases pounds	Weight of Those Parts of a Locomotive Which Are Affected by Changes in Boiler-pressure pounds	Weight of Affected Parts Increased by per cent Given in Column 1 pounds	New Boiler-pressure Obtainable by Utilizing the Increase of Weight in Making a Stronger Boiler, pounds	Steam per Indicated Horse-power per Hour at the Pressures Given in Column 2, pounds	Steam per Indicated Horse-power per Hour at the New Pressures Given in Column 5, pounds	Direct Saving in Steam Consumption Resulting from an Increased Weight Equal to per cent Shown in Column 1, per cent	Indirect Saving Due to Reduced Rate of Evaporation, per cent	Total Saving per cent
1	2	3	4	5	6	7	8	9	10
5	120	55560	58340	150	29.1	27.1	6.87	1.67	8.54
	140	57390	60260	171	27.7	26.3	5.05	1.23	6.28
	160	59220	62180	192	26.6	25.7	3.39	.82	4.21
	180	61050	64100	213	26.0	25.2	3.08	.75	3.83
	200	62880	66020	234	25.5	24.8	2.75	.67	3.42
	220	64710	67940	255	25.1	24.5	2.39	.58	2.97
10	120	55560	61120	181	29.1	26.0	10.65	2.59	13.24
	140	57390	63130	203	27.7	25.4	8.31	2.02	10.33
	160	59220	65140	225	26.6	25.0	6.02	1.46	7.48
	180	61050	67150	247	26.0	24.6	5.38	1.31	6.69
15	120	55560	63890	211	29.1	25.3	13.06	3.17	16.23
	140	57390	66000	234	27.7	24.8	10.46	2.51	13.00
	160	59220	68100	257	26.6	24.5	7.90	1.92	9.82
20	120	55560	66670	241	29.1	24.7	15.12	3.67	18.79

Column 10. Total saving.—The total saving is the sum of Columns 8 and 9.

The significance of this table may best be appreciated by the following examples:

By line 1 of the table it appears that the base is 120 lb. (Column 2). The parts of the typical locomotive designed for this pressure, which are affected by changes in steam-pressure, weigh 55,560 lb. (Column 3). If, now, in designing a new lot of locomotives, it becomes possible to increase this weight by 5 per cent (Column 1), the weight of these parts for the new locomotive may be 58,340 lb. (Column 4). This weight, if put into a boiler of the same capacity, will allow the pressure to be increased from 120 lb. (Column 2) to 150 lb. (Column 5), and as a result its steam con-

sumption per horse-power hour will fall from 29.1 lb. (Column 6) to 27.1 lb. (Column 7), or 6.87 per cent (Column 8). But the saving of 6.87 per cent in steam consumption diminishes the demand which is made upon the boiler for steam, and at the lower rate of evaporation the boiler becomes 1.67 per cent (Column 9) more efficient, giving a total gain as a result of the change in pressure of 8.58 per cent (Column 10). In a similar manner each line of the table presents a measure of the improvement to be expected from some definite increase of pressure.

A study of the analysis which has preceded will show that the values of Column 10 may be accepted as fairly representing the increase in efficiency which may be secured in return for a given increase in steam-pressure, or, as is more clearly shown by Table 4, in return for a given increase in the weight of those parts of the locomotive affected by increase of pressure.

While the comparison is based on improved efficiency, it will, of course, be understood that, at the limit, the saving shown may be converted into a corresponding increase of power. It would have been possible by assuming constant efficiency to have shown the improvement in terms of increase of power.

VII. Boiler Capacity as a Factor in Economical Operations

25. *In the preceding chapter there is considered the advantage to be derived* through the utilization of any possible increase in the weight of a locomotive, as a means by which to secure an increase of pressure. It is the purpose of this chapter to consider the benefit which may be derived by utilizing similar increments in weight to secure an increase in boiler capacity, the pressure remaining constant. The weights of boilers and related parts involved by such a comparison have been ascertained from considerations similar to those which controlled in the preceding case. A boiler of the dimensions already given (paragraph 24), designed for 190 lb., was made the starting-point from which values were ascertained for boilers of different capacities designed to carry 160 lb. pressure. The characteristics of the several boilers thus designed are set forth in Table 6.

TABLE 6

CHARACTERISTICS OF FOUR BOILERS DESIGNED FOR 160 POUNDS PRESSURE AND DIFFERENT CAPACITIES

Diameter of Boiler inches	Number of 2-inch Tubes	Length of Tubes feet	Length of Grate inches	Width of Grate inches	Area of Grate sq. ft.	Area of Heating-surface sq. ft.	Weight of Boiler pounds	Weight of Water in Boiler pounds	Weight of Parts of Locomotive Which Are Affected by Changes in Heating-surface pounds
1	2	3	4	5	6	7	8	9	10
63	258	14	90	60	37.4	2024	30,679	16,349	47,028
67	338	16	102	65	46.1	3013	41,013	20,092	61,105
69	326	14	102	65	46.1	2538	36,321	19,344	55,665
70	396	16	96	75	50.0	3498	42,894	21,965	64,859

The steam-pressure being constant, the dimensions and consequently the weight of the cylinders and related parts for the development of a given power remain unchanged. It is obvious, also, that since the only change in the locomotive is in the size of its boiler, the cylinder performance will be the same for locomotives having boilers of different sizes. The saving which will result from the employment of boilers of greater capacity will be only that which results from the diminished rate of evaporation per unit area of heating-surface. The relation of evaporative efficiency and rate of evaporation has already been defined (Fig. 9), so that both factors in the problem now are known, namely, the increase in weight necessary for a given increase in capacity and the effect of any increase in capacity in improving the evaporative efficiency. By means of relations thus established values have been determined which are presented in Table 7. An explanation of the columns of this table whose meaning is not self-evident is as follows:

Column 3 is the weight of boiler, the contained water, and the cylinders, pistons, and valves. While the cylinders, pistons, and valves do not change for any given pressure, their weights are included to make the values comparable with those employed in the analysis of the preceding chapter. They are in fact identical with the values of Column 3, Table 5.

Column 4. Allowable increase in weight.—The values of this column are the percentages indicated by Column 1 of the values of Column 3.

TABLE 7

SAVING WHEN A POSSIBLE INCREASE OF WEIGHT IS UTILIZED AS A MEANS OF INCREASING HEATING-SURFACE

Increase of Weight per cent	Boiler-pressures Selected as Bases pounds	Weight of Parts of a Typical Locomotive (Boiler, Cylinders, Valves, Pistons, and Water) pounds	Allowable Increase of Weight pounds	Heating-surface of Typical Locomotives Whose Weights Are Given in Column 3 sq. ft.	Increase of Heating-surface Obtainable by Utilizing Increase of Weight in Making a Larger Boiler sq. ft.	Increase of Heating-Surface per cent	Saving in Evaporative Performance Due to Reduced Rate per cent
1	2	3	4	5	6	7	8
5	120	55560	2778	2000	234.7	11.73	2.85
	140	57390	2869	2000	242.5	12.12	2.95
	160	59220	2961	2000	250.1	12.50	3.04
	180	61050	3052	2000	257.7	12.88	3.13
	200	62880	3144	2000	265.3	13.26	3.22
	220	64710	3235	2000	272.9	13.64	3.31
10	120	55560	5556	2000	469.4	23.47	5.70
	140	57390	5739	2000	484.9	24.24	5.89
	160	59220	5922	2000	500.4	25.02	6.08
	180	61050	6105	2000	515.9	25.79	6.27
15	120	55560	8334	2000	704.2	35.21	8.55
	140	57390	8608	2000	727.3	36.36	8.84
	160	59220	8883	2000	750.6	37.53	9.12
20	120	55560	11112	2000	939.0	46.95	11.41

Column 6. Increase of heating-surface.—Values for this column have been obtained by plotting weight of affected parts in terms of heating-surface (Columns 7 and 10, Table 5). The results appear in Fig. 15. From a representative line drawn through points thus obtained showing the relation between the weight of the boiler and water, and the number of square feet of heating-surface, it can be shown that an increase of 10,000 lb. in the weight of boiler and affected parts permits an increase of 845 sq. ft. in heating-surface. Therefore, in Table 6, Column 6 equals Column 4 multiplied by 0.0845. This relation was obtained from data of a boiler designed for 160 lb. pressure and is assumed to be approximately true for boilers of other pressures.

Column 7. Increase of heating-surface, per cent, is Column 6 multiplied by 100 divided by Column 5. It also shows the per cent reduction in the rate of evaporation.

Column 8. Saving in evaporative performance due to reduced rate, per cent.— Values in this column have been obtained from

those of the preceding column by means of a relationship already established controlling evaporative efficiency of boiler and rate of combustion (Fig. 9). This relation is such that a reduction of 1 per cent in the rate of combustion increases the evaporative efficiency 0.243 per cent. Values of Column 8 are, therefore, those of Column 7 multiplied by this factor.

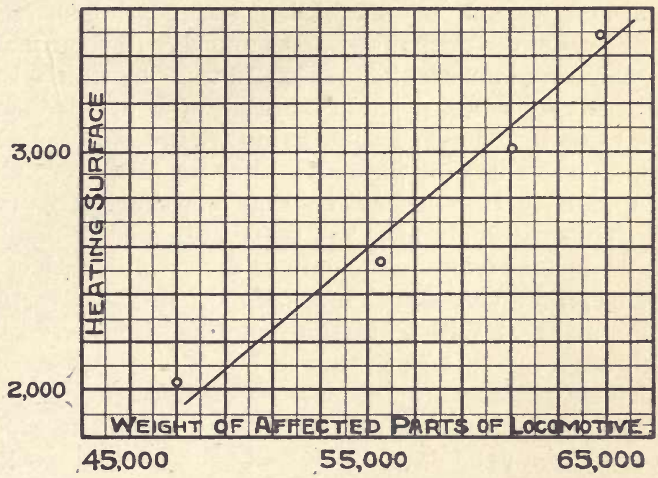

FIG. 15 WEIGHT OF BOILER AS AFFECTED BY CHANGES IN HEATING-SURFACE

The significance of Table 6 will be understood from the following illustration, based upon the first line of the table. Assuming an existing locomotive operating under a pressure of 120 lb. (Column 2) to have a boiler containing 2000 sq. ft. of heating-surface (Column 5) weighing with the contained water 55,560 lb. (Column 3), an increase of 5 per cent (Column 1) or 2778 lb. (Column 4), will permit an extension in heating-surface of 234.7 sq. ft. (Column 6) which, compared with its original surface is an increase of 11.73 per cent (Column 7). This increase in the extent of heating-surface, assuming the power developed to remain unchanged, will result in an improvement in the performance of the boiler of 2.86 per cent (Column 8). The facts underlying the analysis are primarily the results of tests.

VIII. Conclusions Concerning Boiler-Pressure *vs.* Boiler Capacity As a Means of Increasing the Efficiency of a Single-Expansion Locomotive

26. *In the preceding chapters an analysis has been given showing the saving* which may result in locomotive service, first, by increasing the pressure, the boiler capacity remaining unchanged, and second, by increasing the heating-surface, the pressure remaining unchanged. A summary of the conclusions of these chapters is presented in Fig. 16 to 21 in which the full line represents the gain through increase of boiler-pressure and the dotted line the corresponding gain through increase of boiler capacity. The values for these diagrams are taken directly from Tables 5 and 7. It will be seen that starting with pressures which are comparatively low, the most pronounced results are those to be derived from increments of pressure. With each rise in pressure, however, the chance for gain through further increase diminishes. With a starting-point as high as 180 lb., the saving through increased pressure is but slightly greater than that which may result through increased boiler capacity.

The fact should be emphasized that the conclusions above described are based upon data which lead back to the question of coal consumption. The gains which are referred to are measured in terms of coal which may be saved in the development of a given amount of power. It will be remembered that conditions which permit a saving in coal will, by the sacrifice of such saving, open the way for the development of greater power, but the question as defined is one concerning economy in the use of fuel. It is this question only with which the diagrams (Fig. 16 to 21) deal.

There are other measures which may be applied to the performance of a locomotive which, if employed in the present case, would show some difference in the real values of the two curves (Fig. 16 to 21). The indefinite character of these measures prevents their being directly applied as corrections to the results already deduced, but their effect may be pointed out. Thus, the extent to which an increase of pressure will improve performance has been defined, but the definition assumes freedom from leakage. If, therefore, leakage is allowed to exist, the result defined is not secured. Moreover, an increase of pressure increases the chance

of loss through leakage, so that to secure the advantage which has been defined, there must be some increase in the amount of attention bestowed, and this, in whatever form it may appear, means expense, the effect of which is to reduce the net gain which it is possible to derive through increase of pressure. Again, in parts of the country where the water-supply is bad, any increase of pressure will involve increased expense in the more careful and more extensive treatment of feed-water, or in the increased cost of boiler repairs, or in detentions arising from failure of injector, or from all of these sources combined. The effect of such expense is to reduce the net gain which it is possible to derive through increase of pressure. These statements call attention to the fact that the gains which have been defined as resulting from increase of pressure (Fig. 16 to 21) are to be regarded as the maximum gross; as maximum because they are based upon results derived from a locomotive which was at all times maintained in the highest possible condition, and as gross because on the road, conditions are likely to be introduced which will necessitate deductions therefrom.

The relation which has been established showing the gain to be derived through increased boiler capacity is subject to but few qualifying conditions. It rests upon the fact that for the development of a given power a large boiler will work at a lower rate of evaporation per unit area of heating-surface than a smaller one. The saving which results from diminishing the rate of evaporation is sure; whether the boiler is clean or foul, tight or leaky, or whether the feed-water is good or bad, the reduced rate of evaporation will bring its sure return in the form of increased efficiency. An increase in the size of a boiler will involve some increase in the cost of maintenance, but such increase is slight and of a sort which has not been regarded in the discussion involving boilers designed for higher pressures.

Keeping in mind the fact that as applied to conditions of service the line *A* is likely to be less stable in its position than *B*, the facts set forth by Fig. 16 to 21 may be briefly reviewed.

Basing comparisons upon an initial pressure of 120 lb., (Fig. 16), a 5 per cent increase in weight, when utilized in securing a stronger boiler, will improve the efficiency 8.5 per cent, while if utilized in securing a larger boiler, the improvement will be a trifle less than 3 per cent. Arguing from this base, the advantage

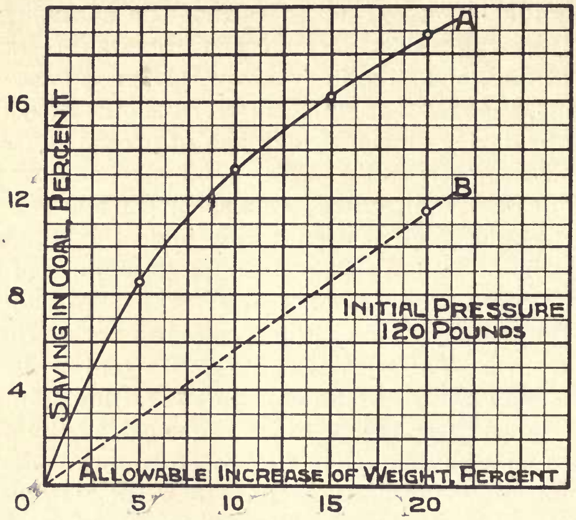

FIG. 16

The line A represents the saving in fuel when an allowable increase in weight is utilized in making a stronger boiler to permit a higher pressure.
The line B represents the saving in fuel when an allowable increase in weight is utilized in making a larger boiler to give increased capacity.

to be derived from an increase of pressure is great. If, however, the increase in weight exceeds 10 per cent, the curve *A* ceases to diverge from *B* and if both curves are sufficiently extended, they will meet, all of which is proof of the fact that the rate of gain is greatest for relatively small increments of weight.

Basing comparisons upon an initial pressure of 140 lb. (Fig. 17), the relative advantage of increasing the pressure diminishes, though on the basis of a 5 per cent increase in weight it is still double that to be obtained by increasing the capacity.

Basing comparisons upon an initial pressure of 160 lb. (Fig. 18), the advantage to be gained by increasing the pressure over that which may be had by increasing the capacity is very small, so small in fact that a slight droop in the curve of increased pressure (*A*) would cause it to disappear. As the curve *B* may be regarded as fixed, while *A*, through imperfect maintenance of boiler or engine, may fall, the argument is not strong in favor of increasing pressure beyond the limit of 160 lb.

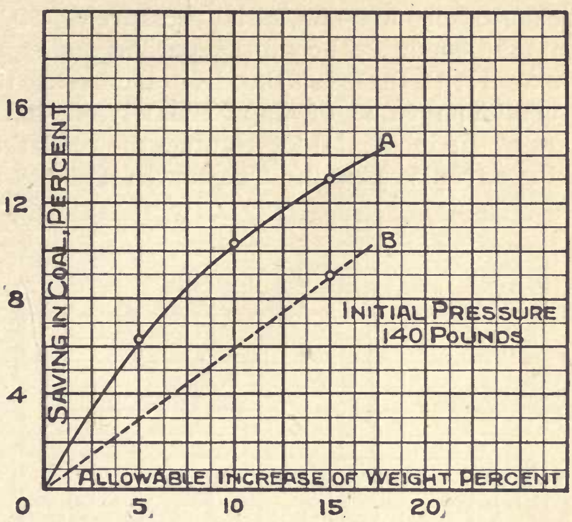

FIG. 17

The line A represents the saving in fuel when an allowable increase in weight is utilized in making a stronger boiler to permit a higher pressure.

The line B represents the saving in fuel when an allowable increase in weight is utilized in making a larger boiler to give increased capacity.

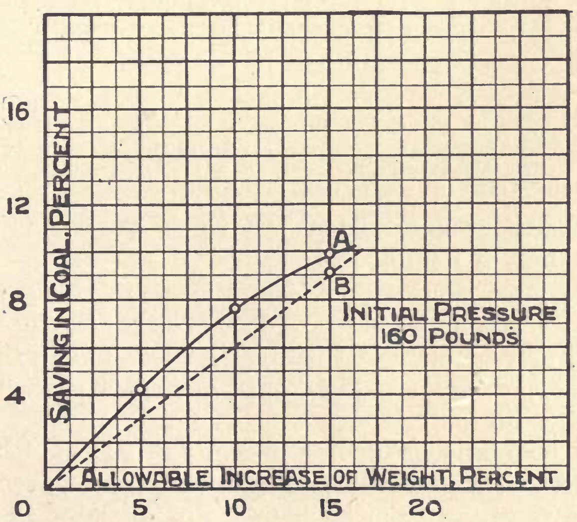

FIG. 18

The line A represents the saving in fuel when an allowable increase in weight is utilized in making a stronger boiler to permit a higher pressure.

The line B represents the saving in fuel when an allowable increase in weight is utilized in making a larger boiler to give increased capacity.

Basing comparisons upon an initial pressure of 180 lb., (Fig. 19), the advantage under ideal conditions of increasing the pressure, as compared with that resulting from increasing the capacity, has a maximum value of approximately one-half of 1 per cent. In view of the incidental losses upon the road the practical value of the advantage is nil. The curves *A* and *B* (Fig. 12),

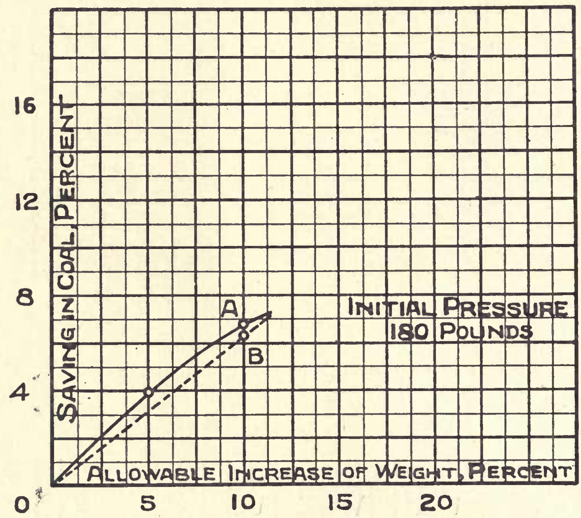

FIG. 19

The line A represents the saving in fuel when an allowable increase in weight is utilized in making a stronger boiler to permit a higher pressure.

The line B represents the saving in fuel when an allowable increase in weight is utilized in making a larger boiler to give increased capacity.

constitute therefore no argument in favor of increasing pressure beyond the limit of 180 lb.

Basing comparisons upon an initial pressure of 200 lb., (Fig. 20), it appears that under ideal conditions either the pressure or the capacity may be increased with equal advantage, this being in effect a strong argument in favor of increased capacity rather than of higher pressure.

Basing comparisons upon a pressure of 220 lb., (Fig. 21), it appears that even under ideal conditions of maintenance the gain in efficiency resulting from an increase of pressure is less than that resulting from an increase of capacity. In view of this fact, no possible excuse can be found for increasing pressure above the limit of 220 lb.

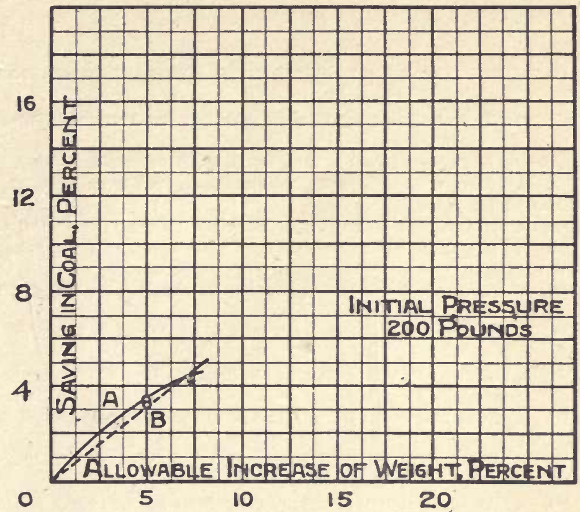

FIG. 20

The line A represents the saving in fuel when an allowable increase in weight is utilized in making a stronger boiler to permit a higher pressure.

The line B represents the saving in fuel when an allowable increase in weight is utilized in making a larger boiler to give increased capacity.

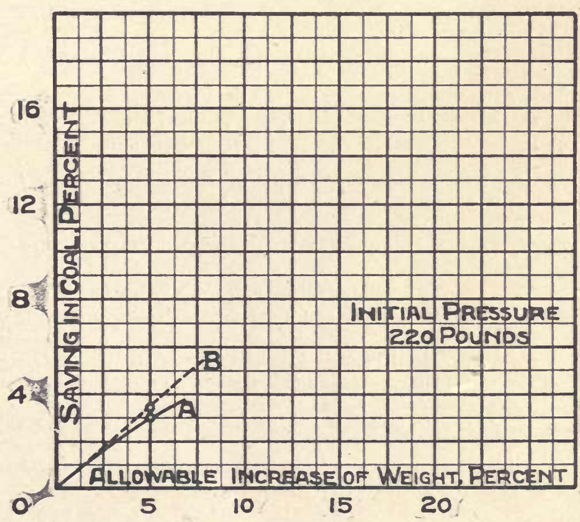

FIG. 21

The line A represents the saving in fuel when an allowable increase in weight is utilized in making a stronger boiler to permit a higher pressure.

The line B represents the saving in fuel when an allowable increase in weight is utilized in making a larger boiler to give increased capacity.

Publications of The Engineering Experiment Station

Bulletin No. 1. Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904. (*Out of print.*)

Circular No. 1. High-Speed Tool Steels, by L. P. Breckenridge. 1905.

Bulletin No. 2. Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905.

Circular No. 2. Drainage of Earth Roads, by Ira O. Baker. 1906. (*Out of print.*)

Bulletin No. 3. The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906. (*Out of print.*)

Bulletin No. 4. Tests of Reinforced Concrete Beams, Series of 1905, by Arthur N. Talbot. 1906.

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Bulletin No. 6. Holding Power of Railroad Spikes, by Roy I. Webber. 1906. (*Out of print.*)

Bulletin No. 7. Fuel Tests with Illinois Coals, by L. P. Breckenridge, S. W. Parr and Henry B. Dirks. 1906.

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Bulletin No. 9. An Extension of the Dewey Decimal System of Classification Applied to the Engineering Industries, by L. P. Breckenridge and G. A. Goodenough. 1906.

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